APPENDIX 7-C. LIFE-CYCLE COST ENERGY USE CALCULATIONS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX 7-C. LIFE-CYCLE COST ENERGY USE CALCULATIONS

7-C.1 INTRODUCTION

This appendix contains the methodology for calculating the energy use of residential water heaters, direct heating equipment, and pool heaters in the life-cycle cost (LCC) analysis.

7-C.2 WATER HEATERS

Water heater energy consumption is calculated using the Water Heater Analysis Model (WHAM) equation.[1] Figure 7-C.2.1 shows the WHAM methodology.

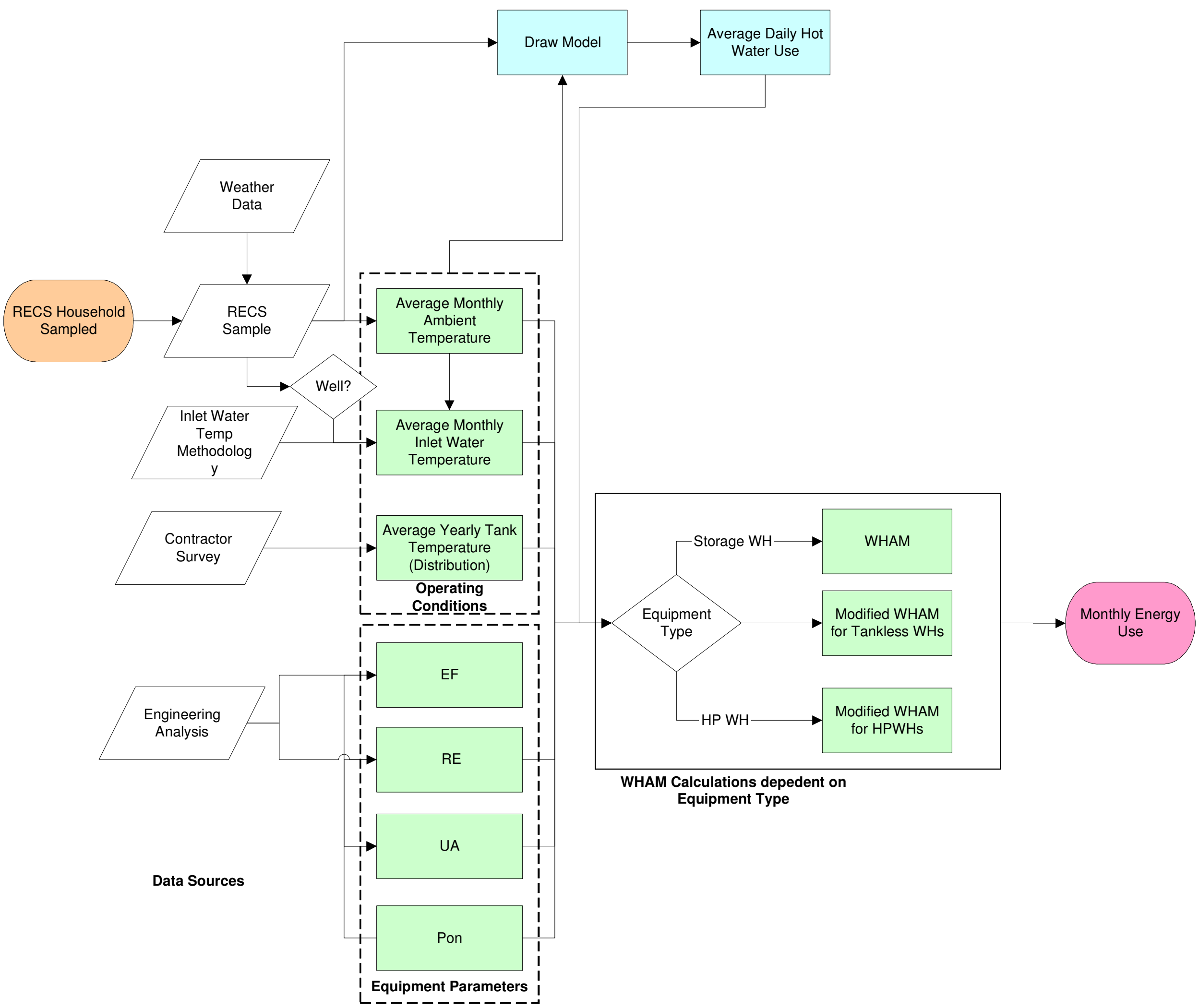

Figure 7-C.2.1 Methodology for Calculating Energy Consumption for Water Heaters

7-C.2.2 WHAM Equation

The WHAM equation[1] yields average daily water heater energy consumption (Q_{in}), and is expressed as follows:

$$Q_{in} = \frac{vol \times den \times C_P \times (T_{tank} - T_{in})}{RE} * \left(1 - \frac{UA \times (T_{tank} - T_{amb})}{P_{on}}\right) + 24 \times UA \times (T_{tank} - T_{amb})$$

Where:

Q_{in} =	total water heater energy consumption, Btu/day,
RE =	recovery efficiency, %,
P_{on} =	rated input power, Btu/h,
UA =	standby heat-loss coefficient, Btu/h-^{o}F,
T_{tank} =	thermostat setpoint temperature, ^{o}F,
T_{in} =	inlet water temperature, ^{o}F,
T_{amb} =	temperature of the air surrounding the water heater, ^{o}F,
vol =	volume of hot water drawn in 24 hours, gal/day,
den =	density of stored water, set constant at 8.29 lb/gal, and
C_p =	specific heat of stored water, set constant at 1.000743 Btu/lb-^{o}F.

For gas-fired storage water heaters, gas-fired instantaneous water heaters, and oil-fired storage water heaters, it is necessary to disaggregate electricity and fuel consumption. Figure 7-C.2.2 shows the methodology for calculating electricity and fuel consumption using WHAM. DOE calculated electricity consumption as follows:

$$Q_{electtricity} = \frac{Q_{in}}{P_{ON}} \times \left(P_{aux} - P_{s\tan dy}\right) - P_{s\tan dy} \times 24$$

Where:

$Q_{electricity}$ =	electricity consumption, kWh,
Q_{in} =	total water heater energy consumption, Btu/day,
P_{ON} =	rated input power, kW,
P_{aux} =	electricity demand when burner is on, kW, and
P_{standy} =	electricity demand when burner is off, kW.

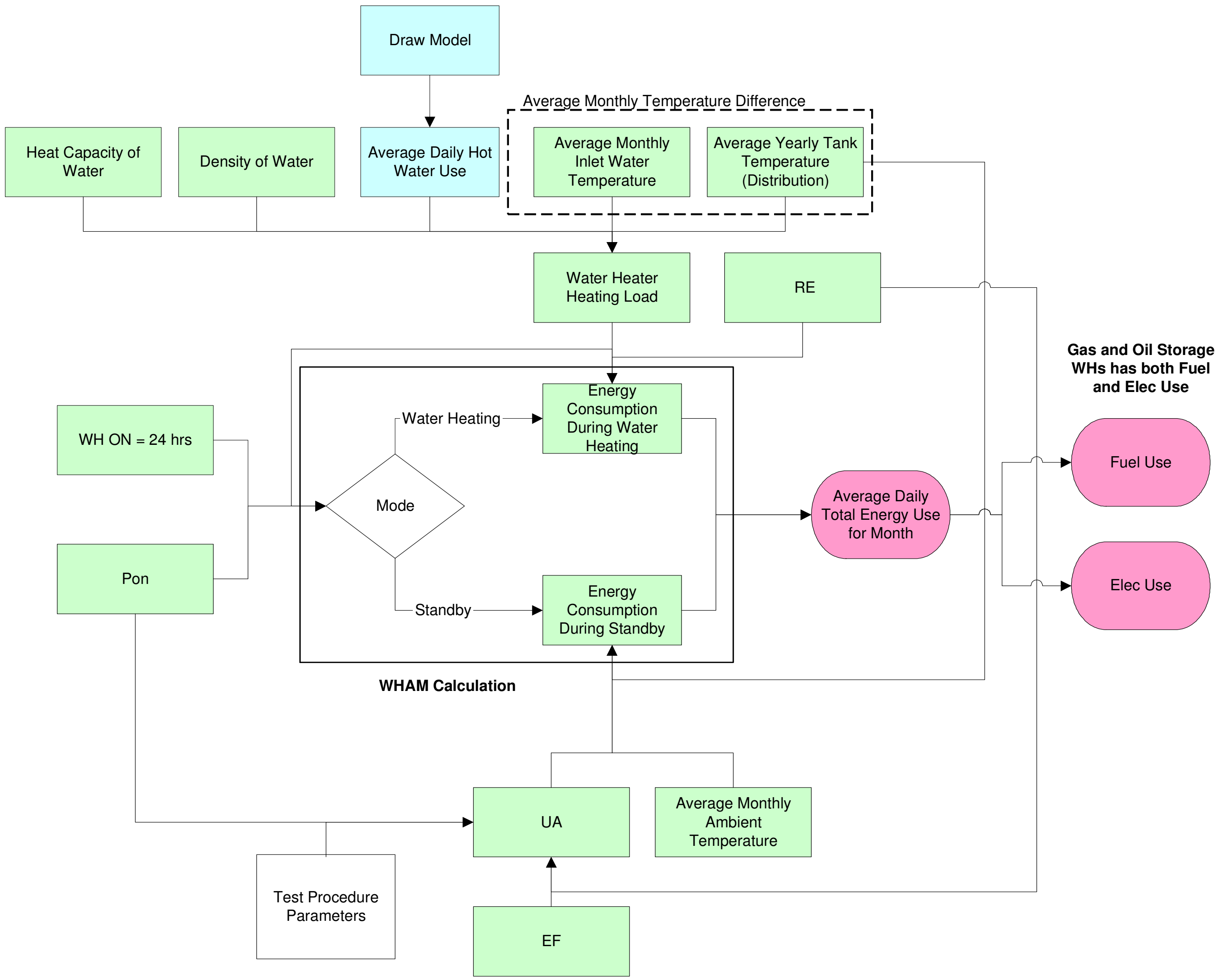

Figure 7-C.2.2 Methodology for Calculating Storage Water Heater Energy Consumption using WHAM Equation

DOE calculated gas consumption by subtracting electricity consumption from total water heater energy consumption (Q_{in}). Figure 7-C.2.3 shows the methodology for calculating electricity and fuel consumption for gas and oil storage water heaters.

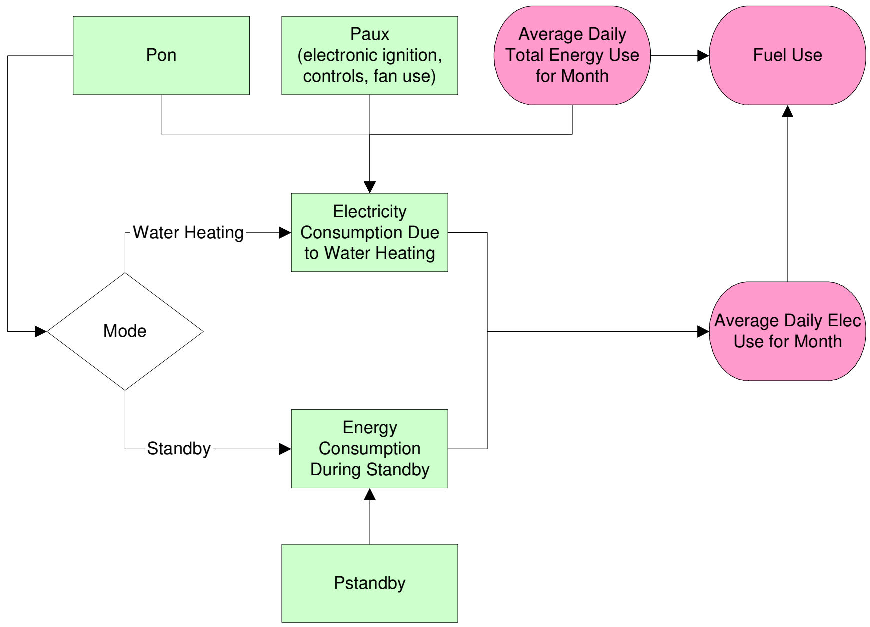

Figure 7-C.2.3 Methodology for Calculating Electricity and Fuel Consumption for Gas and Oil Storage Water Heaters

7-C.2.3 WHAM Equation for Heat Pump Water Heaters

For heat pump water heaters, energy efficiency and consumption are dependent on ambient temperature. To account for this factor, DOE expanded the WHAM to utilize the calculation approach used in the New York State Energy Research and Development Authority (NYSERDA) heat pump water heater site screening tool and DOE's weatherization assistance program.[2, 3] The equation for determining the energy consumption of heat pump water heaters is similar to the WHAM equation, but a performance adjustment factor that is a function of the average ambient temperature is applied to adjust *RE*. A heat pump water heater operates either in heat pump or in electric resistance mode. DOE assumed that the electric resistance mode of operation is used 100 percent of the time when the monthly ambient temperature is less than 32 ^{o}F or more than 100 ^{o}F. A heat pump water heater also operates in the electric resistance mode for part of the time even when the monthly ambient temperature is between 32 ^{o}F and 100 ^{o}F, because this product has a slower recovery rate than an electric resistance water heater. DOE determined that, depending on household hot water consumption patterns, the electric resistance mode of operation occurs for as much as 10 percent of the unit's operating time. Figure 7-C.2.4 shows the methodology for calculating the energy consumption of HPWHs using the modified WHAM equation.

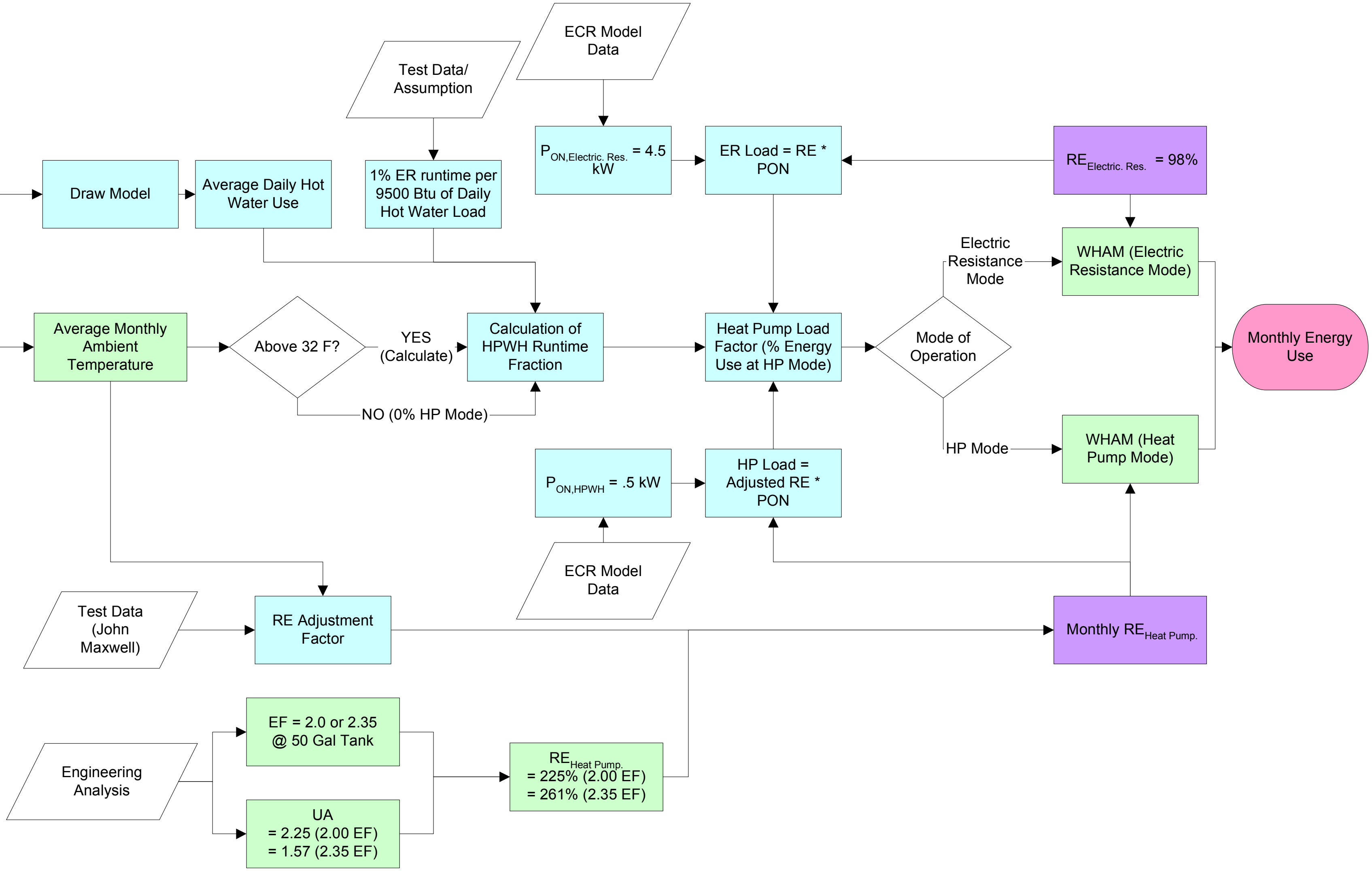

Figure 7-C.2.4 Methodology for Calculating HPWH Energy Consumption using Modified WHAM Equation

The HPWH WHAM equation is as follows:

$$Q_{in} = vol \times den \times C_P \left(T_{\tan k} - T_{in}\right) \times \left[\begin{array}{l} \dfrac{HP\_frac}{RE_{HPWH} \times PA_{hpwh}} \times \left(1 - \dfrac{UA \times \left(T_{\tan k} - T_{amb}\right)}{P_{ON,HPWH}}\right) + \\ \dfrac{(1 - HP\_frac)}{RE_{ER}} \times \left(1 - \dfrac{UA \times \left(T_{\tan k} - T_{amb}\right)}{P_{ON,ER}}\right) \end{array} \right] + 24 \times UA \times \left(T_{Tank} - T_{amb}\right)$$

Where:

Q_{in} =	total water heater energy consumption, Btu/day,
vol =	daily draw volume, gal/day,
den =	density of water, set constant at 8.29 lb/gal,
C_p =	specific heat of water, set constant at 1.000743 Btu/lb-°F,
T_{tank} =	tank thermostat set point temperature, °F,
T_{in} =	inlet water temperature, °F,
RE_{HPWH} =	recovery efficiency of heat pump mode, %,
RE_{ER} =	recovery efficiency of electric resistance mode, %,
UA =	standby heat-loss coefficient, Btu/h-°F,
T_{amb} =	temperature of the air surrounding the water heater, °F,
$P_{ON,HPWH}$ =	rated input power of heat pump mode, Btu/h,
$P_{ON,ER}$ =	rated input power of electric resistance mode, Btu/h,
PA_{hwh} =	performance adjustment factor, $0.00019738 \times T_{amb}^2 - 0.01842 \times T_{amb} + 1.3222625$, and
HP_frac =	fraction of water heating load that is satisfied by heat pump mode.

HP_frac is calculated using the following equation:

$$HP\_frac = \frac{HP_{on} \times P_{ON,HPWH} \times RE_{HPWH} \times PA_{hpwh}}{HP_{on} \times P_{ON,HPWH} \times RE_{HPWH} \times PA_{hpwh} + (1 - HP_{on}) \times P_{ON,ER} \times RE_{ER}}$$

Where:

HP_{ON} =	fraction of time when heat pump mode is operating, %, $\left(100 - \dfrac{vol \times den \times C_P \left(T_{\tan k} - T_{in}\right)}{9500}\right)$, when T_{amb}>32ºF and 0 when T_{amb}<32 ºF.
$P_{ON,HPWH}$ =	rated input power of heat pump mode, Btu/h,
$P_{ON,ER}$ =	rated input power of electric resistance mode, Btu/h,
RE_{HPWH} =	recovery efficiency of heat pump mode, %,
RE_{ER} =	recovery efficiency of electric resistance mode, %,
PA_{hwh} =	performance adjustment factor, %, $0.00019738 \times T_{amb}^2 - 0.01842 \times T_{amb} + 1.3222625$, and
T_{amb} =	temperature of the air surrounding the water heater, °F.

7-C.2.3.1 Comparison of energy use calculations for heat pump water heaters

The energy use calculation used by DOE in this analysis is slightly different from either the NYSERDA Heat Pump Water Heater Site Screening Tool or DOE's weatherization assistance program.

DOE's weatherization assistance program calculates HPWH energy use by using the following formula:

$$Q_{in} = \frac{vol \times den \times C_P \left(T_{\tan k} - T_{in}\right)}{EF \times (1 + PA)}$$

Where:

Q_{in} = total water heater energy consumption, btu/day,
vol = daily draw volume, gal/day,
den = density of water, lb/gal,
C_p = specific heat of water, Btu/lb-^{o}F,
T_{tnk} = tank thermostat set point temperature, ^{o}F,
T_{in} = inlet water temperature, ^{o}F,
EF = energy factor, and
PA = performance adjustment factor, %.

The performance adjustment factor is calculated by using the following formula:

$$PA = 0.00008 \times T_{amb}^3 + 0.0011 \times T_{amb}^2 - 0.4833 \times T_{amb} + 0.0857, \text{when } T_{\text{amb}} > 32^o F$$

$$PA = \frac{1}{EF} - 1, \text{when } T_{\text{amb}} \leq 32^o F$$

The New York State Energy Research and Development Authority (NYSERDA) Heat Pump Water Heater Site Screening Tool calculates HPWH energy use by using the following formula:

$$Q_{in} = vol \times den \times C_P \left(T_{\tan k} - T_{in}\right) \times \left[\begin{array}{l} \frac{lfhp}{EF_{hpa}} \times \left(1 - \frac{UA \times \left(T_{\tan k} - T_{amb}\right)}{P_{HP}}\right) + \\ \frac{(1 - lfhp)}{EF_r} \times \left(1 - \frac{UA \times \left(T_{\tan k} - T_{amb}\right)}{P_r}\right) \end{array} \right] + 24 \times UA \times \left(T_{Tank} - T_{amb}\right)$$

Where:

Q_{in} = total water heater energy consumption, Btu/day,
Vol = daily draw volume, gal/day,
den = density of water, lb/gal,
C_p = specific heat of water, Btu/lb-^{o}F,
T_{tank} = tank thermostat set point temperature, ^{o}F,

T_{in} = inlet water temperature, ^{o}F,
UA = standby heat-loss coefficient, Btu/h-^{o}F,
T_{amb} = temperature of the air surrounding the water heater, ^{o}F,
P_{HP} = rated input power of heat pump mode, Btu/h,
P_R = rated input power of electric resistance mode, Btu/h,
EF_r = resistance mode energy factor,
EF_{hpa} = heat pump mode adjusted energy factor,
$EF_{hp} \times \left(0.00019738 \times T_{amb}^{2} - 0.01842 \times T_{amb} + 1.3222625\right)$, and
$lfhp$ = fraction of water heating load that is satisfied by heat pump mode, %,

$$\frac{rthp \times P_{HP} \times EF_{hpa}}{rthp \times P_{HP} \times EF_{hpa} + (1 - rthp) \times P_R \times EF_R}$$

$rthp$ = fraction of run time by heat pump mode (96.4%).

Table 7-C.2.1 shows a comparison of energy use results for the DOE modified WHAM method used in this analysis, the NYSERDA Heat Pump Water Heater Site Screening Tool method, and DOE's weatherization assistance program method.

Table 7-C.2.1 Comparison of 2.0 EF HPWH Energy Use Results

Calculation Methodology	Average Annual Energy Use *(kWh/y)*	% Diff from method used in this analysis
DOE modified WHAM	1399	-
NYSERDA method	1505	+7.6%
Weatherization program	1142	-18.4%

7-C.2.3.2 Calculating HPWH Cooling Effects

Heat pump water heaters draw heat from the space in which they are located. Thus, when such a water heater is located in a conditioned space, its use affects the load that the home's space heating and air conditioning equipment must meet. When the home is being heated, use of the heat pump water heater increases the heating load, and when the house is being cooled, its use decreases the cooling load.

In some cases, a household will choose to install a venting system to deal with the above situation. DOE believes this would occur to 50% of the houses where the cooling load produced by the heat pump water heater in the heating season is large (greater than 3 MMBtu/year). In the remaining cases, DOE believes the household would not want to incur the cost of a venting system, and would instead operate their heating and cooling systems to compensate for the effects of the heat pump water heater. To account for these indirect effects of heat pump water heaters on home energy use, DOE estimated the impact on space heating and air conditioning energy consumption for some of the homes in the RECS electric water heater subsample that have the water heater in the conditioned space.

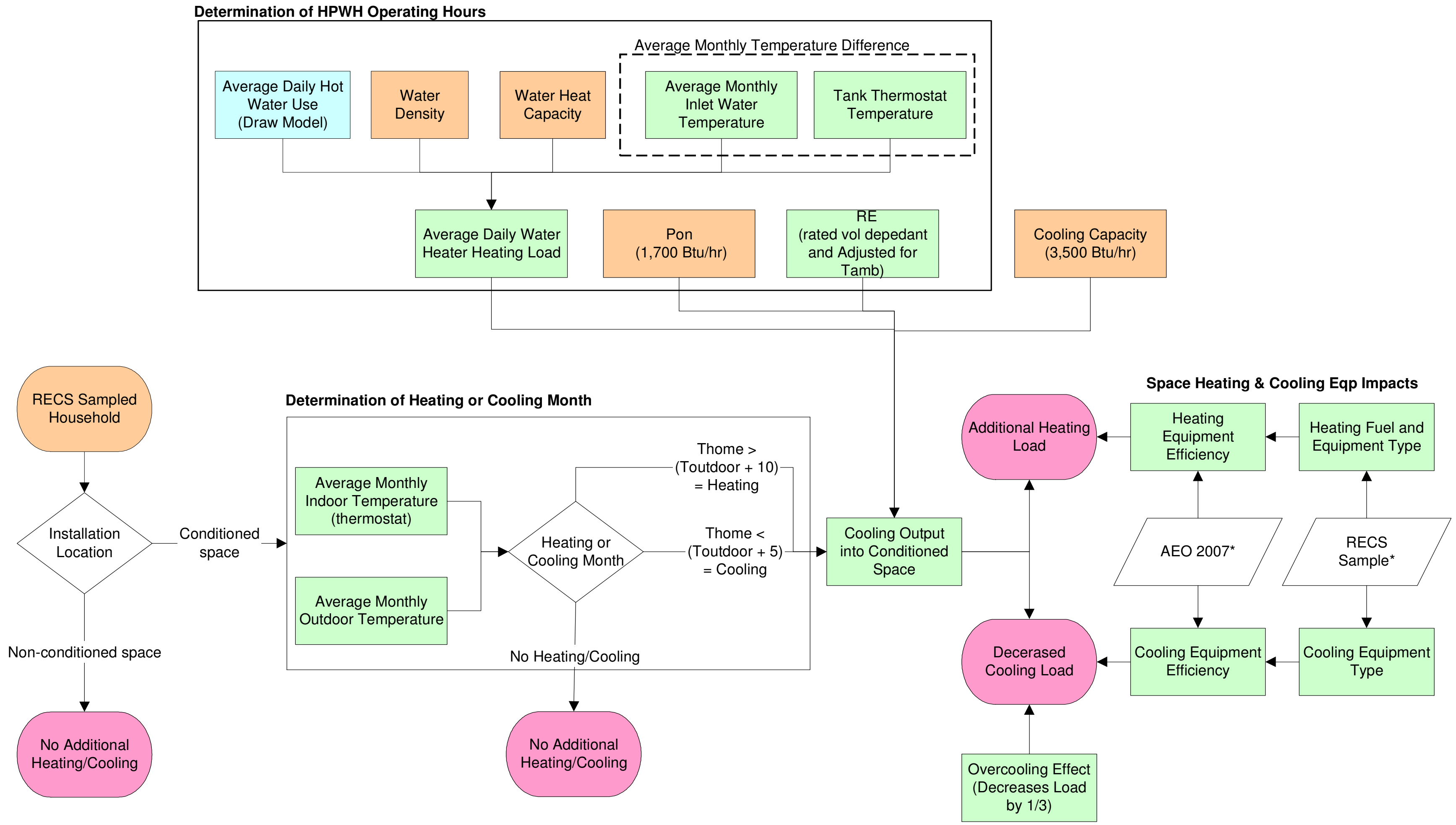

Figure 7-C.2.5 Methodology for Calculating HPWH Cooling Effect

For each such home, DOE estimated the impact on space heating in heating months only (when indoor temperature is 10 degrees greater than the average outdoor temperature), and the impact on air conditioning for cooling months only (when indoor temperature is 5 degrees less than the average outdoor temperature). Figure 7-C.2.5 shows the methodology DOE used to calculate the amount of cooling added (i.e., heat removed) by the heat pump water heater.

DOE calculated the amount of cooling added (heat removed) by the heat pump water heater as follows:

$$CoolingInput = CoolingCap_{HPWH} \times \frac{vol \times den \times C_p \left(T_{\tan k} - T_{in}\right)}{P_{ON,HPWH} \times RE_{HPWH} \times PA_{HPWH}}$$

Where:

$CoolingInput$ =	amount of cooling added by the HPWH, Btu/h,
vol =	daily draw volume, gal/day,
den =	density of water, lb/gal,
C_p =	specific heat of water, Btu/lb-^{o}F,
T_{tank} =	tank thermostat set point temperature, ^{o}F,
T_{in} =	indoor air temperature, ^{o}F,
$P_{ON,HPWH}$ =	rated input power, Btu/h,
RE =	recovery efficiency, %,
PA_{hwh} =	performance adjustment factor, %, and
$CoolingCap_{HPWH}$ =	cooling capacity of heat pump water heater, Btu/h.

For the P_{ON} and cooling capacity of the heat pump water heaters DOE created distributions that apply for a range of possible HPWH designs. Based on a consultant report, cooling capacity for HPWHs was determined to vary from 3200 to 4200 Btu/h.[4] A uniform distribution was used to describe this range (with a mean value of 3700 Btu/h). The cooling capacity is estimated to be 2/3 of heating capacity (e.g., for mean cooling capacity value of 3700 Btu./h this results in 5550 Btu/h heating capacity). Pon is calculated using heating capacity and the COP of the HPWH. DOE used a COP value of 3.0 for this calculation. DOE used this COP value for HPWH having efficiencies of 2.0 EF (e.g., for mean cooling capacity value of 3700 Btu./h and 5550 Btu/h heating capacity, this results in Pon of 1850 Btu/h = 542 Watts). To account for the increase in efficiency for HPWHs at 2.35 EF, DOE adjusted the Pon value by multiplying by a fraction equal to the ratio of RE between 2.0 HPWH and 2.35 HPWH (e.g. continuing with the example, Pon of the 2.35 HPWH would be 86 percent of the 2.0 HPWH = 1591 Btu/h = 466 Watts).

DOE used RECS 2005[5] data for each household to determine the primary heating system, type of heating fuel used, and cooling system type. DOE then assigned an energy efficiency to each type of equipment to determine the energy use loss (from heating) or gain (from cooling). DOE based the energy efficiency of the heating and air conditioning equipment on the stock-average values for 2015 given in EIA's *Annual Energy Outlook 2010*.[6] To account for the times during the summer months when the air conditioner is not operating (e.g., at night), DOE reduced the estimated cooling benefits from the water heater by one-third (8 out of 24 hours).

The analysis results that the HPWH cooling effect affects 40.1 percent of households for an average of 6.2 months in the heating season and 21.9 percent of households for an average of 5.4 months in the cooling season. Overall 44.2 percent of households are affected either in cooling and/or heating season (or about 90 percent of indoor or heated basement installations). The average net cost from heating is about $93 per year, while the average net benefit for cooling is about $6 per year. These impacts are accounted for in the LCC and NIA analysis.

Alternatively, as explained above, the household can install a venting system to vent the cold air out of the conditioned space. DOE estimates that the average cost for this installation would be similar to the average cost of adding a new plastic venting system for condensing furnaces which is found in the 2007 Furnace and Boilers Rulemaking.[7] (See Appendix 8-A for more details)

7-C.2.4 WHAM Equation for Gas Instantaneous Water Heaters

For instantaneous water heaters, DOE calculated the energy use using a similar approach to storage water heaters, but modified to account for the absence of storage tank and adjusted for the performance observed in the field compared to that measured with the DOE test procedure. Figure 7-C.2.7 shows the methodology for calculating the energy consumption of instantaneous water heaters using the modified WHAM equation.

For instantaneous water heaters, DOE utilized the approach used for storage water heaters to calculate the energy use, modified to account for the absence of storage tank. DOE applied a performance adjustment factor to account for results from studies of instantaneous water heater performance under field conditions.[8, 9, 10, 11] Preliminary results from a study of instantaneous water heater installations conducted for the California Energy Commission (CEC) under field conditions at single-family two-occupant residence indicated higher energy use than under the test procedure conditions. The report concludes that the discrepancy is due to the extra losses at small draw volumes.[8] The other studies have shown a similar effect. DOE's approach used data from GTI and CEC studies to derive the adjustment factor as a distribution of values as a function of the household hot water use.

To account for this phenomenon, DOE used test data from TIAX to come up with a relationship between hot water consumption and decreased performance as shown in the figure 7-C.2.6 for the 0.82 EF unit tested using typical U.S. household draw patterns. DOE set an upper limit on the performance factor equal to the CEC recommended Energy Factor (EF) reduction for gas-fired instantaneous water heaters of 8.8 percent and a lower limit of 0%.

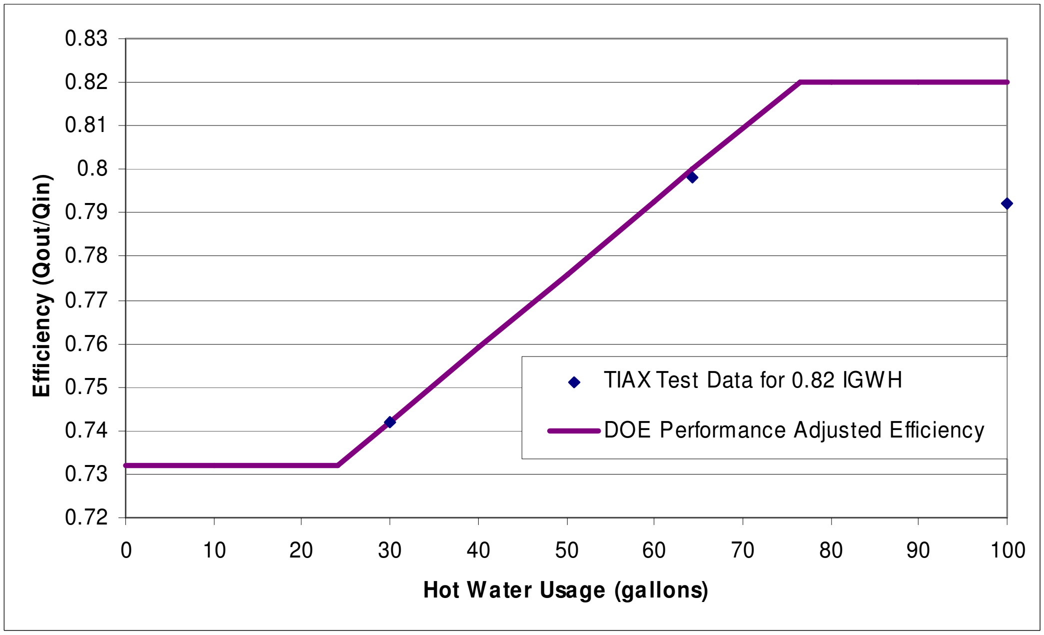

Figure 7-C.2.6 Efficiency versus Hot Water Usage for Instantaneous Gas Water Heater rated at 0.82 EF

The instantaneous water heater WHAM equation is as follows:

$$Q_{in} = \frac{vol \times den \times C_P (T_{\tan k} - T_{in})}{RE \times (1 + PA_{iwh})} \times \left(1 - \frac{Q_p}{P_{ON}}\right) + 24 \times Q_p \times (T_{Tank} - T_{amb})$$

Where:

Q_{in} =	total water heater energy consumption, Btu/day,
vol =	daily draw volume, gal/day,
den =	density of water, lb/gal,
Cp =	specific heat of water, Btu/lb-^{o}F,
T_{tank} =	tank thermostat set point temperature, ^{o}F,
Tin =	inlet water temperature, ^{o}F,
RE =	recovery efficiency, %,
PA_{iwh} =	performance adjustment factor, %,
Q_p =	pilot input rate, Btu/h,
Q_{out} =	heat content of the water drawn from the water heater, Btu/h, and
Pon =	rated input power, Btu/h,.

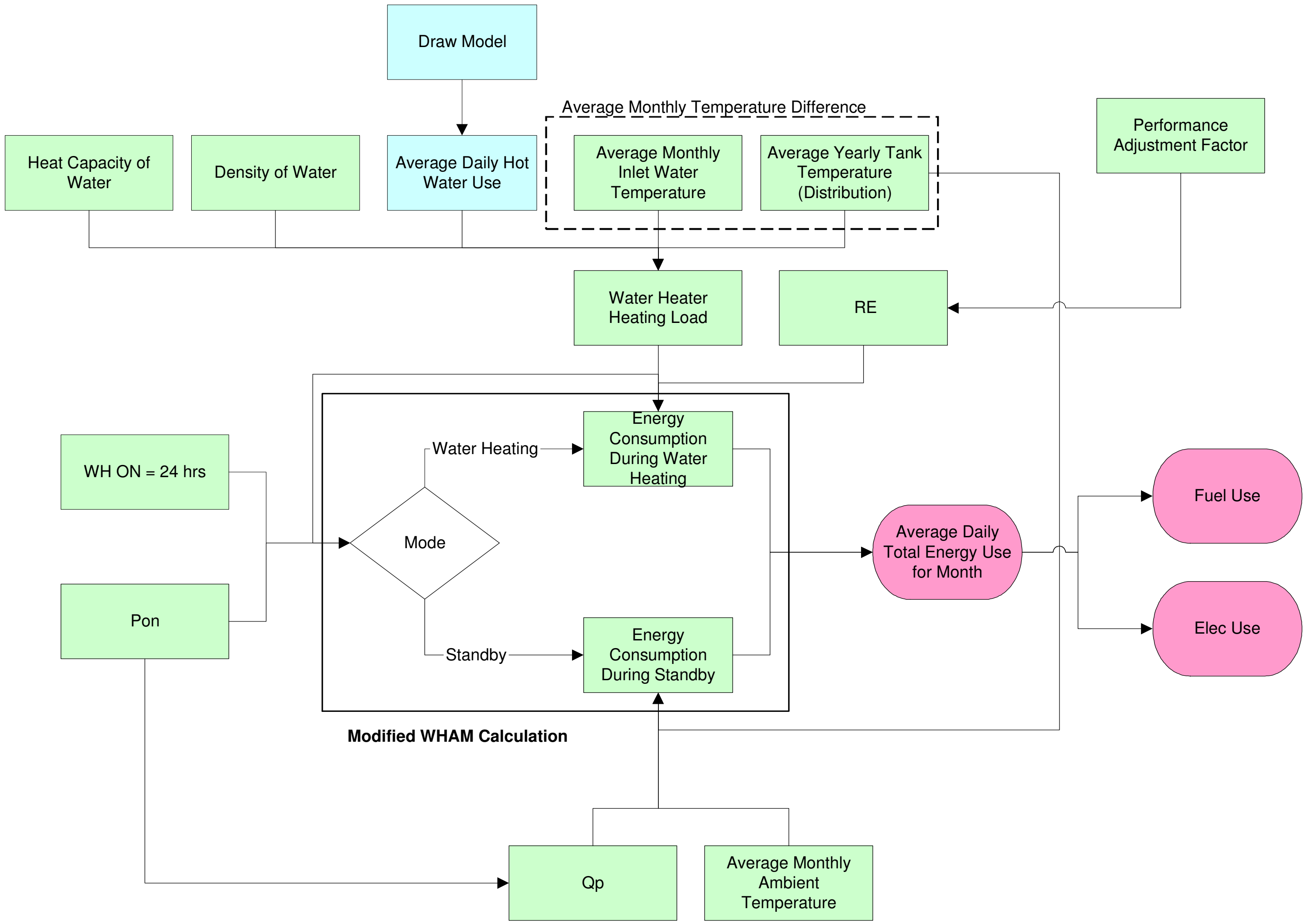

Figure 7-C.2.7 Methodology for Calculating Instantaneous WH Energy Consumption using Modified WHAM Equation

The performance adjustment factor for instantaneous water heaters (PA_{iwh}) was derived from a study conducted for the California Energy Commission (CEC) in 2006.[8] According to this report, current DOE test procedure energy factor calculations for gas-fired instantaneous water heaters overvalue their performance by neglecting the impact of small hot water draws and heat exchanger "cool down" on overall performance. The DOE test procedure measures six successive draws of approximately 10 gallons, while actual field use has many more small draws. The 8.8 percent adjustment factor is derived using average hot water use profiles and weighting by more efficient "hot starts" and less efficient "cold starts".

7-C.3 POOL HEATERS

DOE calculated the average annual fossil fuel energy, E_F, using the DOE test procedure:[12]

$$E_F = BOH \times Q_{IN} - (POH - BOH) \times Qp$$

Where:

BOH = burner operating hours, h/year,
Qin = pool heater input rate, kBtu/h,
POH = pool operating hours, h/yr, and
Qp = pilot light input rate, kBtu/yr.

The burner operating hours are calculated using the pool heater heating load (PHHL) for each sample household. The equation for BOH is as follows:

$$BOH = \frac{LOAD}{Q_{IN} \times E_t}$$

Where:

BOH = burner operating hours, h/year,
$PHHL$ = pool heater heating load, btu/year, (see Appendix G),
Q_{in} = pool heater input rate, kBtu/h, and
E_t = thermal efficiency.

DOE calculated the electricity consumption using the following formula

$$E_F = BOH \times PE - (POH - BOH) \times PE_{s\tan by}$$

Where:

BOH = burner operating hours,
PE = electrical consumption of the heater,
POH = pool operating hours (h/yr), and
PE_{stby} = electrical consumption of the heater when the burner is off.

7-C.4 DIRECT HEATING EQUIPMENT

DOE calculated the average annual fuel energy, E_F, for single-stage direct heating equipment using the following formula from the current revision of DOE's test procedure:[13]

$$E_F = BOH_{SS} \times (Q_{IN} - Q_P) + 8760 \times Q_P$$

Where:

BOH =	burner operating hours, h/year,
Q_{in} =	input capacity (at the max input rate), kBtu/h,
8760 =	hours per year, and
Q_p =	pilot light input rate, kBtu/h.

The burner operating hours are calculated using the calculated house heating load (HHL) for each sample household (see Appendix G). The equation for BOH is as follows:

$$BOH_{SS} = A \times HHL - 4160 \times Q_P \times \eta_U ,$$

Where:

BOH_{SS} =	burner operating hours, h/year,
A =	$\dfrac{100{,}000}{341{,}000 \times PE + (Q_{in} - Q_P) \times \eta_U}$,
HHL =	house heating load (see Appendix G), btu/year,
PE =	maximum electric power, kW,
4160 =	average heating season hours,
Q_P =	pilot light input rate, kBtu/h,
η_U =	$\dfrac{2950 AFUE \times \eta_{SS} \times Q_{in}}{2950 \times \eta_{SS} \times Q_{in} - AFUE \times 2.033 \times 4600 \times Q_P}$, and
η_{SS} =	steady state efficiency, %.

The steady state efficiency (η_{SS}) is calculated by solving for η_{SS} in the equation given in section 4.1.17 of the DOE test procedure using the following equation and the values for the parameters D_F, D_S, P_F, and L_J given in the DOE test procedure:

$$\eta_{SS} = \frac{AFUE + 1.78 \times D_F + 189 \times D_S - 129 \times P_F - 2.8 \times L_J + 1.81}{0.968}$$

The electricity consumption is calculated as follows:

$$ElectUse = BOH \times PE + (8760 - BOH) \times P_{stby}$$

Where:

ElecUse =	DHE electricity consumption, kWh/year,
BOH =	burner operating hours, h,
PE =	electricity demand when the product is firing, kW, and
P_{stby} =	DHE standby power draw (when the burner is OFF), kW.

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